An approach to provide maps of the N2O emission risks by soils at the regional scale: A case-study at the Haut-Loir watershed, France

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1   **Title**:

2   An approach to provide maps of the N_2O emission risks by soils at the regional scale: a case-study at
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15   **Highlights:**

16   A methodology is developed to map N_2O emission risk based on soil properties.

17   The hazard and the vulnerability allow inferring the risk of N_2O emissions

18   This methodology is relevant for all types of soil dedicated to agriculture

19   Areas where N_2O emissions mitigation actions are possible have been identified.

20

21   **Abstract:**

22   Nitrous oxide (N_2O) is often emitted by soils after nitrogen fertilization when the reduction of nitrate

23   into N_2 is incomplete and the soil is in hydromorphic condition. To take action to reduce N_2O

24   emissions, it is necessary to identify and locate areas that present a risk of N_2O emissions. In this

25   study, an approach to map N_2O emission risk by soils was therefore developed based on soil

26   properties. The risk of N_2O emission was assessed through two components linked to static properties,

27   independent on climate and agricultural practices; the Vulnerability: the ability of the soil to reduce

28   N_2O and the Hazard: the probability of soil water-logging. This approach was tested in the Haut-Loir

29   watershed (3600 km²), a highly cropped area in the French Center Region. Vulnerability and hazard

30   were estimated using French soil databases. The databases contain the drainage class information

31   which allowed inferring the hazard. They also have measurements of pH, CEC and clay content which

32 allowed estimating vulnerability through a pedotransfer function. In this watershed, contrasting risks

33 were highlighted between different soil types and agricultural regions. High risk soils (~2% of the

34 studied area) were generally found in valleys and were not under crop because of their hydromorphy

35 and acidity. However, attention should be given to medium risk soils (~32% of the area) which were

36 mainly found in the western region. Oppositely, soils of the eastern region present generally no risk of

37 N_2O emissions. Some former field studies have been reported in the studied watershed: they generally

38 supported this soil risk classification. For medium-risk soils, different actions of mitigation depending

39 on the degree of risk were suggested: liming or adjusting nitrogen input periods. This risk mapping

40 approach could be applied in other cropland regions to help mitigation strategy.

41

42 **Keywords***:*

43 Greenhouse gas; Risk assessment; Vulnerability; Hazard; Exposure; Soil mapping; Multiple soil
44 classes.

45

46 **Abbreviations:**

47 CEC, Cation Exchange Capacity; GHG, Greenhouse Gas; HV, High Vulnerability; HH, High Hazard;
48 HR, High Risk; IPCC, Intergovernmental Panel on Climate Change; Km, Kilometers; LV, Low
49 Vulnerability; LH, Low Hazard; LR, Low Risk; MM, Moderate Vulnerability; MH, Moderate Hazard;
50 MR, Moderate Risk; RP (French), Pedological Referential; RRP, Pedological Regional Referential;
51 STU, Soil Typological Units; SMU, Soil map Units; WRB, World Reference Base for soil resources.
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1. Introduction

Climate change induced by increased Greenhouse Gases (GHGs) emissions in the atmosphere results in global warming (Masson-Delmotte et al., 2018). Nitrous oxide (N_2O) is one of the three main anthropogenic GHGs in the atmosphere. N_2O has about 265 times the warming potential of CO_2 (Ciais et al., 2013), but its concentration is more than 1000 times lower than atmospheric CO_2 concentration, so its contribution to the greenhouse effect is evaluated for 2020 at about 7% against 66% for CO_2 and 16% for CH_4 (WMO, 2021). In France, agriculture is the main sector contributing to anthropogenic N_2O emissions and represented about 89% of these emissions in 2019 (Thompson et al., 2019; CITEPA, 2021). Agricultural emissions of N_2O are mainly due to N inputs of mineral and organic fertilizers in soils and a linear relation is assumed between N inputs and N_2O emissions (1% of N input, IPCC Tier-1, Hergoualc'h et al., 2019). In France, since 1990, N_2O emissions have been slightly decreased, from 65.4 to 38.2 Mt CO_2e, and emission due to agriculture decreased slowly from 38.2 to 34.5 Mt CO_2e (CITEPA, 2021), thanks to the use of more optimized and regulated mineral fertilizers. The "Centre – Val de Loire" region is a region of intensive agriculture where the contribution of agriculture to total N_2O emissions is estimated to be as high as 95% (2.6 Mt CO_2e) corresponding to about 14% of all GHGs in CO_2e (LIG'AIR inventory V2.4/2020).

Agricultural N_2O emissions exhibit a very large spatial and temporal variability because they are highly dependent on pedoclimatic conditions (e.g., soil concentration of mineral nitrogen, soil moisture, temperature). The N_2O is indeed produced by several microbial processes resulting from the activity of different species of microorganisms (e.g., nitrification, denitrification, nitrifier denitrification…; Butterbach-Bahl et al., 2013) using soil nitrogen as substrate. Denitrification (the reduction of nitrate in several steps, to N_2O and lastly to N_2) is considered as one of the most important processes of N_2O production in soils (Dobbie and Smith, 2001). Denitrification occurs in anoxic soils and is therefore favored by soil moisture. Large peaks of N_2O emissions occur in wet soils with high nitrogen (N) levels, usually after input of nitrogen fertilizers (Stehfest and Bouwmann, 2006; Ito et al., 2018). Complete denitrification leads to N_2 emission, which is not of environmental concern since N_2 is a non-reactive molecule and is not absorbing in the infrared spectrum. The last

82 step of denitrification, the reduction of N_2O in N_2, is inhibited in certain soil conditions or in some

83 soils. Therefore, some soils do not present a capacity to reduce N_2O to N_2. For example, pH controls

84 the ability of the denitrifying bacteria to express N_2O reductase early and efficiently (Russenes et al.,

85 2016), which probably explains why soil pH influences N_2O emissions when denitrification is the

86 main source of N_2O. Previous studies also revealed soil pH as one of the main factors governing

87 regional variability of N_2O emission on a global meta-analysis (Wang et al., 2018). Many studies have

88 been conducted to understand the determinism of N_2O production and reduction, bringing more and

89 more insight into these processes and their controlling factors (Stehfest and Bouwman, 2006; Cui et

90 al., 2021) and the effect of different agricultural practices. This enables to propose some technical

91 solutions to limit N_2O emissions. Avoiding excess soil nitrate, particularly when soils are too wet, can

92 help minimize N_2O emissions from agriculturally managed soils. Other solutions are being studied,

93 like bacterial seeding, draining moist soil, nitrification-inhibiting (e.g. Henault et al., 1998; Rochette,

94 2008; Ruser and Schulz, 2015; Hinton et al., 2015). pH management, i.e. soil liming to raise the pH, is

95 also an important track to reduce N_2O emissions (Henault et al., 2019; Shaaban et al., 2020).

96 However, most studies have been made at field scale, so the representativeness of observations when

97 upscaling (e.g. regional scale) is unclear. N_2O is indeed produced at soil microsite scale and this

98 production is controlled by a complex interaction of factors. Therefore, similar agricultural practices

99 can have different effect on N_2O emission in different soil types (e.g. Rochette et al., 2008). The use of

100 methods to reduce N_2O emissions involve identifying soils which are likely to emit N_2O. This is

101 consistent with the findings of Cui et al. (2021), who recently provided a global map of N_2O emission

102 factors (i.e. N_2O emission taking into account nitrogen inputs) based on a data-driven meta-analysis.

103 They outlined that the most policy-relevant question is to identify where emissions can be mitigated

104 more efficiently.

105 It is therefore useful to provide maps of N_2O emissions or emission risk which can indicate where

106 actions have to be taken. Few studies provide spatial assessment of emissions and they generally

107 consider agricultural practices, which can be difficult to obtain. Mapping N_2O emission can be done

108 by applying predictive models: this approach was used by the European Soil Data Centre, who

109　published a map of N_2O emissions from agricultural soil in Europe taking soil properties into account,

110　based on LUCAS soil sampling program and using DayCent model combined with random forest

111　approach (Lugato et al., 2017). The resulting map depends on climatic data inputs and information on

112　managements practices. As N_2O emissions are extremely dependent on climatic conditions, they

113　averaged 5 years of data to smooth the temporal variability. Another method was proposed by Kritee

114　et al. (2018) who mapped risk of large N_2O emissions from rice production taking into account two

115　components: water management regimes and regional N fertilizer rates, but ignoring soil properties. In

116　both cases, the maps are a snapshot of a given situation as climate and management practices are

117　subjected to change. Providing soil N_2O emission risk, based on soil properties, i.e. static or more or

118　less static properties, is a valuable approach for policy-makers. This is consistent with the approach of

119　Cui et al. (2021): they provided a global map of emission factors rather than N_2O emissions. Global

120　information may however have a too coarse resolution for defining mitigation strategies; the best scale

121　would be regional or national, which is also the scale of policy-making. However, Cui et al. (2021)

122　also observed that controlling factors are scale-dependent, so it is very important to further provide

123　regional maps of N_2O emission risk.

124　The objective of this paper was therefore to develop an approach to map at regional scale N_2O

125　emission risk based on soil properties. IPCC approach defined risk as the likelihood of harmful

126　alterations due to hazardous physical events interacting with vulnerable conditions (Lavell et al.,

127　2012). They proposed to cross hazard, vulnerability and exposure to fully assess risk, and defined

128　these three notions. Hazard is the potential occurrence of a physical event having adverse effect;

129　vulnerability is the predisposition of an element to be affected due to internal characteristics; and

130　exposure referred to the presence of resources in places that could be affected by the physical events.

131　A similar approach is then developed here for N_2O emission risk. Hazard was considered as soil water

132　excess probability, which leads to conditions favorable to denitrification. Vulnerability was considered

133　to be due to the soil capacity to reduce N_2O in N_2, which, as already mentioned, depends on soil

134　properties. Exposure corresponds to soil nitrogen inputs. In this study, vulnerability and hazard were

135　considered simultaneously to provide maps considering only static risk in relation to soil properties.

136 Soil capacity to reduce N_2O to N_2 can be evaluated in the laboratory, using incubated soil samples

137 according to ISO/TS 20131-2 method (Le Gall et al., 2014; Henault et al., 2019). An index, called r-

138 max value, is calculated, which corresponds to the ratio between the amount of N_2O emitted without

139 and with acetylene during incubation because acetylene inhibits the last step of denitrification. The

140 higher is the r-max, the lower is the soil's ability to reduce N_2O to N_2. The r-max value can also be

141 estimated by a soil function depending of pH, Cation Exchange Capacity (CEC) and clay content,

142 where pH is the more relevant variable of function (Henault et al., 2019). This function was applied on

143 soil databases. Hazard was assessed by the natural soil hydromorphic class.


144 Providing N_2O emission risk assessment is especially important in intensive cropland areas receiving

145 large fertilizations. The present approach was thus applied in an intensive cropland region of France.

146 The first step was to map the r-max index using the pedotransfer function and soil variables from a

147 French Soil database. In a second step, the risk approach was tested to assess graduated soil N_2O

148 emissions risk based on the combination of vulnerability and hazard. A former dataset was also used

149 to assess the validity of the soil risk classification. Therefore, this study aims to contribute and

150 improve existing tools and approaches to provide at decision-scale N_2O emission maps from existing

151 soil databases.

152 **2. Materials and methods**

153

154 2.1. The study area

155 The study area is a watershed in the upper valley of Loir River "Haut-Loir", located in French "Centre

156 Val-de-Loire" region France, that has already been the support of several studies on direct and indirect

157 N_2O emissions (Gu et al., 2013; Grossel et al., 2016; Billen et al., 2018, 2020). It extends over 3600

158 km² and includes seven agricultural regions: Perche, Faux Perche, Beauce, Beauce Dunoise, Orléanais,

159 Val de Loire and Vallée de Loir (Figure 1). The four main regions (Perche, Faux Perche, Beauce,

160 Beauce Dunoise) represent 90% of the study area and are covered by intensive croplands – usually

161 wheat, barley, maize and rapeseed - that are subjected to high nitrogen inputs.

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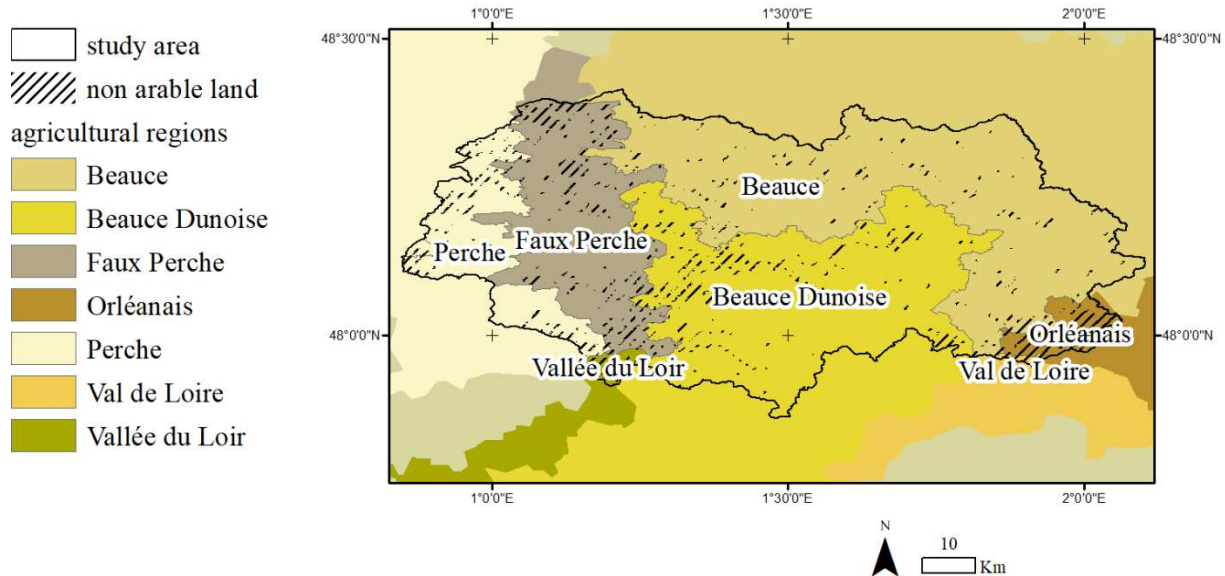
Figure 1: Haut-Loir extension, study area

163

164　The Loir River consists in a natural limit between the Eastern Beauce/Beauce Dunoise regions and the

165　Western Perche/Faux Perche regions. For the purposes of this regional study, the soil classification

166　was kept in its original repository (RP2008, Baize et al., 2009) described in the French database

167　(Figure 2). The correspondence between the RP2008 and the WRB soil classifications is given in the

168　Appendix A. The match is not easy between the two systems of classification because a soil described
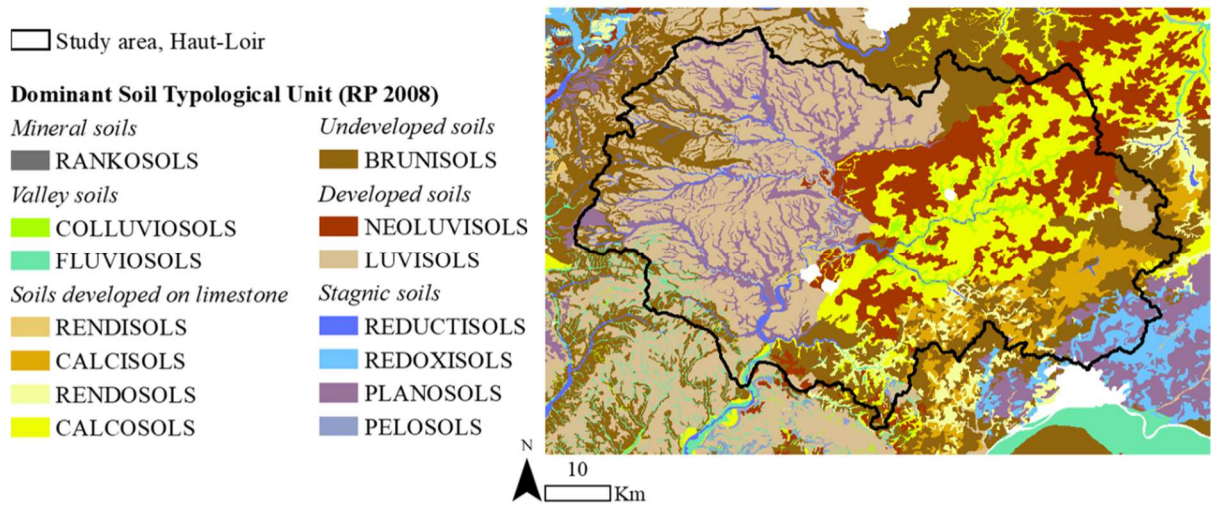
169　in RP2008 can have several matchings in WRB and vice versa. The correspondence depends on many

170　possibilities of qualifying soils that have not been further analysed in this study due to the lack of

171　representativeness at this regional scale.

172

173   *Figure 2: Haut-Loir soils map. Soils are given in regional repository and the correspondence to WRB*

174   *is given in Appendix A.*

175   The Western Perche and the Vallée du Loir Region are dominated by hydromorphic LUVISOLS and

176   PLANOSOLS, which are usually drained and limed for agriculture practices (Figure 2).

177   REDUCTISOLS are usually located near streams. In the Beauce/Beauce Dunoise regions, soils are

178   developed on limestone (CALCOSOLS, CALCISOLS and NEOLUVISOLS …): they are more clayey

179   and exhibit a higher pH value. Agricultural soils in these Eastern areas are usually irrigated, which

180   allows maize plant in crop rotation. Orléanais forest region, in the Southwest part of the study area,

181   and the Val-de-Loire Region, are dominated by PLANOSOLS and REDOXISOLS. The white areas in

182   the soils map (Figure 2) correspond to undefined soil (urban areas) where there is no data in DoneSol.

183

184   2.2. The soil database

185   We have used a French Soil Geographical database on a scale of 1:250,000: "Référentiels Régionaux

186   Pédologiques", RRPs (Richer-de-Forges et al., 2019). RRPs are regional geographic databases

187   established from field surveys and observations by soil scientists. The data from RRPs are available to

188   users through a national standardized soil information storage system (DoneSol).

189   Donesol contains a list of Soil Typological Units (**STU**). In RP2008, STU are described by variables

190   specifying the soil type and their properties (soil texture, CEC, pH, soil drainage, etc.). Soil natural

191   drainage is coded from 1 (well-drained soils) to 9 (submerged soils) (Richer-de-Forges et al., 2019; *cf.*

192   Table 1, supplementary material). This indicator provides information on the frequency of excess

193   water in the soil.

194   At the scale of 1:250,000, it is not possible to delineate the STUs. Therefore, they are grouped into

195   Soil Mapping Units (SMU) to form soil associations and to illustrate the functioning of pedological

196   systems in landscapes. Each SMU corresponds to soil-landscape, i.e. a part of the mapped territory

197   defined by specific pedology, hydrogeology, topology and / or land use. It has a known shape and

198   location and is represented by one or more polygons in a geometrical dataset. Oppositely, STU cannot

199 be precisely located within SMU. Soil type (STU) can be identified within SMU and is specified as a

200 percentage of SMU area. As a result, RRPs consists of both a geometrical dataset defining SMU and a

201 semantic dataset which links attribute values, including STU and soil variables, to the SMUs. It is the

202 same principle than for Soil Geographical Database of Europe, well-illustrated in the supplementary

203 Figure 1.

204 For display purpose, the SMU properties are represented with either the dominant STU, or a weighted

205 average of STU areas. Both methods were tested in this study. Database structure is explained in the

206 following link:

207 (https://esdac.jrc.ec.europa.eu/ESDB_Archive/ESDBv2/esdb/sgdbe/metadata/purity_maps/purity.htm.

208

209 2.3. R-max index

210 The r-max index, indicative of the capacity of a soil to reduce N_2O to N_2, was calculated for each STU

211 by using soil variables (CEC, pH and clay content) from the DoneSol database according to the

212 following function (Henault et al., 2019 and ISO/TS 20131-2 norm):

213 *r-max = -0.4 pH + 0.026 CEC - 0.001 clay + 3.13 (r = 0.88)*

214 where pH is evaluated on an air-dried sample suspended in water according to the NF ISO 10390

215 norm, CEC is evaluated on a soil sample extract using a cobalt-hexamine solution (Orsini and Rémi,

216 1976) according to the NF X 31-130 norm, and clay represents the clay content $(g.g^{-1})$ measured on a

217 soil sample without decarbonation by using the Robinson pipette method according to the NF X 31-

218 107 norm. The r-max values are limited to 1.2.

219 According to Hénault et al., 2019, soils with an *r-max* > 0.8 have a very low capacity to reduce N_2O,

220 soils with *r-max* < 0.4 are able to reduce N_2O and soils with an *r-max* value between 0.4 and 0.8 have

221 an intermediate capacity to reduce N_2O. Soil pH explains most of the *r-max* index variability (61%):

222 soils with pH < 6.4 have usually *r-max* > 0.8, and soils with pH > 6.8 have r-max < 0.4, (Hénault et al.,

223 2019).

224   2.4. Definition of N_2O emission risk

225 Risk of N_2O emission was based on Hazard, Vulnerability and Exposure as suggested in literature

226 (Crichton, 1999; Wolf, 2012; Lavell et al., 2012).

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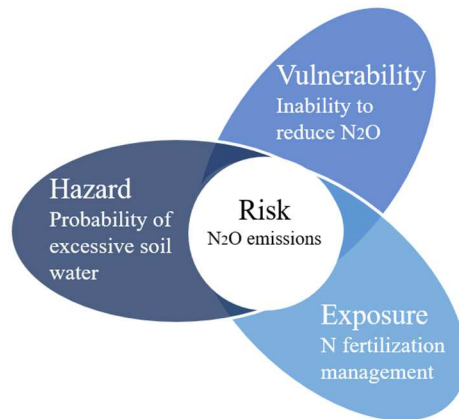
Figure 3: representation of N_2O emission risk, inspired by core concept of SREX IPCC, 2012

229 In our case (Figure 3) Vulnerability corresponds to the soil inability to reduce N_2O, natural Hazard is

230 the probability that a situation of excess water occurs, and Exposure corresponds to N fertilization by

231 farmers, leading to an increase in available mineral N into the soil. Hazard can be predicted thanks to

232 precipitations or soil water content measured by in situ sensors. Exposure could be limited by

233 decreasing N inputs. Exposure depends on land use: croplands were considered as the only ones that

234 are subject to nitrogen inputs related to fertilization. For urban area or forest, Exposure is zero.

Soil water excess		Capacity to reduce N_2O		
		Low Vulnerabilty r-max <0.4	Moderate Vulnerability 0.4<r-max<0.8	High Vulnerability r-max>0.8
	Low Hazard 1,2,3	Low Risk	Low Risk	Low Risk
	Moderate Hazard 4,5,6	Low Risk	Moderate Risk ❶	Moderate Risk ❷
	High Hazard 7,8,9	Low Risk	High Risk ❸	High Risk ❹

Prevision climate

Mitigation Soil pH management

Limitation Nmin inputs management

235

236 *Figure 4: N₂O risk core concept*

237 Three classes of Vulnerability were defined: Low Vulnerability (LV) for *r-max* < 0.4, Moderate

238 Vulnerability (MV) for 0.4<*r-max*<0.8 and High Vulnerability (HV) for *r-max* >0.8. Hazard, i.e.

239 probability of excess water in soils, depends not only on precipitations but also on soil type. Soil

240 drainage class was thus considered to identify areas where excess water may occur. Three classes of

241 Hazards were similarly defined: Low Hazard (LH) for DoneSol soil drain classes 1, 2 and 3, Moderate

242 Hazard (MH) for classes 4, 5 and 6 and High Hazard (HH) for classes 7, 8 and 9. Finally, we defined

243 risk by crossing vulnerability with hazard (Figure 4). However, hazard and vulnerability, as defined,

244 are not controlling N_2O emission risk in the same way. Excess water controls the occurrence of

245 denitrification, i.e. N_2O production in soils. The soil capacity to reduce N_2O in N_2 is important only if

246 denitrification and N_2O production can occur, i.e. if there is significant hazard. This is why hazard was

247 considered to have a higher control on risk than vulnerability and the figure 4 is not fully symmetrical.

248 In other words, moderate Risk (MR) corresponds at situations of Moderate Hazard with Moderate or

249 High Vulnerabilities and High Risk (HR) corresponds at situations of High Hazard with Moderate or

250 High Vulnerabilities.

251 Last four risk categories were defined to suggest different mitigation strategies. Vulnerability can be

252 reduced by actions of mitigation. For example, liming soils raises the pH and increases the soil's

253 ability to reduce N_2O (Henault et al., 2019). Categories 1 (moderate risk) and 3 (high risk) correspond

254 to situations of moderate vulnerability that can mostly be mitigated by liming soil when pH < 6.8.

255 Categories 2 and 4 correspond respectively to Moderate Risk and High Risk that can be reduced by

256 liming soil when pH < 6.4 and that further requires special precautions when supplying nitrogen in soil

257 (dose reduction or taking account soil water condition).

258 2.5 Validation data

259 N_2O emission measurements from previous studies (Hénault et al., 2005; Franqueville et al., 2018 and

260 other unpublished studies) were used to validate the present approach. These measurements were

261 carried out over thirteen study sites included in our study area "Haut-Loir".

262 Thus, N$_2$O emissions and soil properties are available from direct measurements for one CALCISOLS,

263 six LUVISOLS, two BRUNISOLS and four COLLUVIOSOLS. N$_2$O measurements were done by

264 static chamber with a frequency varying from once per week to once per month.

265 All plots were cropped with winter cereals and fertilized with mineral N but at different timing,

266 splitting and amount. Therefore, to compare sites, N$_2$O emissions were cumulated from the last date

267 before first fertilization to one month after the last fertilization. N$_2$O peaks generally occur in the

268 weeks following N inputs so this may encompass most of the fertilization effect. The ratio of

269 cumulative emission during post-fertilization period to the N input amount was then calculated for all

270 sites.

271 Measured r-max values following the protocol of Hénault et al. (2019) were reported when available

272 (measured r-max index). A Calc. r-max index was calculated from soil properties measured on in situ

273 soil samples during the studies and STU r-max index was calculated from the Donesol values of the

274 map soil STU. Drainage classes were inferred from Donesol database. This allowed to assess hazard

275 and vulnerability and to calculate a risk class for each site.

276

277 **3. Results and discussion**
278

279   3.1. Application of the *r-max* function at STU and SMU resolution

280   3.1.1.*r-max* index computed by STU

281 DoneSol semantic database was used to infer the *r-max* values for all STU with the values of clay.

282 CEC and pH (85% of STU). This allowed to assess an *r-max* value (Table 1) for each soil type of the

283 study site and thus infer its vulnerability typology (ability to reduce N$_2$O to N$_2$).

284 *Table 1: r-max mean value by soil type and associated standard deviation (std). number (nb) of values*
285 *in each STU and SMU. representativeness in study site (% area) and vulnerability typology.*

Soil type (RP2008)	nb STU	r-max mean	r-max std	% area	nb SMU	Vulnerability

CALCOSOLS (CALCO)	23	0.11	0.13	10	25	LV
RENDOSOLS (RENDO)	11	0.14	0.14	3	22	LV
RENDISOLS (RENDI)	5	0.17	0.16	1	10	LV
HISTOSOLS* (HIST)	1	0.25		<1	1	LV
CALCISOLS (CALCI)	18	0.29	0.19	6	26	LV
FLUVIOSOLS (FLUV)	19	0.42	0.26	<1	9	MV
PEYROSOLS (PEYR)	1	0.44		<1	1	MV
COLLUVIOSOLS (COLL)	10	0.51	0.36	1	7	MV
NEOLUVISOLS (NEO)	18	0.58	0.21	12	20	MV
BRUNISOLS* (BRUN)	51	0.61	0.31	14	45	MV
ARENOSOLS (ARE)	1	0.62		<1	2	MV
PELOSOLS (PEL)	3	0.63	0.10	<1	2	MV
LUVISOLS (LUV)	50	0.64	0.22	28	32	MV
FERSIALSOLS (FER)	1	0.74		<1	1	MV
PLANOSOLS (PLANO)	10	0.78	0.09	8	15	MV
REDOXISOLS (REDOX)	6	0.80	0.37	2	11	HV
VERTISOLS (VERT)	1	0.86		<1	1	HV
REDUCTISOLS (REDUCT)	5	0.88	0.28	1	3	HV
ALOCRISOLS (ALO)	1	1.20		<1	1	HV
PODZOSOLS (PODZ)	2	1.20	0.00	<1	2	HV

286

287

288 The *r-max* mean values vary from 0.11 (CALCOSOLS, carbonated soil from the surface) to 1.20

289 (PODZOSOLS, acidic soils). Soil types FERSIALSOLS, HISTOSOLS, ARENOSOLS, VERTISOLS

290 and ALOCRISOLS are less encountered in the study area, thus their *r-max* values must be further

291 confirmed.

292 The soils with the lowest *r-max* are soils developed on limestone (RENDOSOLS, CALCOSOLS,

293 RENDISOLS and CALCISOLS). These soils have an *r-max* under 0.4, so they are able to reduce N_2O.

294 They cover 20% of the Haut-Loir surface and they are mostly to the Eastern of the site

295 (Beauce/Beauce dunoise). For the HISTOSOLS the *r-max* value is 0.25. As HISTOSOLS correspond

296 to peat soils (organic soils) and are often acidic, farmed organic soils appear to emit exceptionally

297 large amounts of N_2O (Kasimir-Klemedtsson et al., 1997). However, in this study the only

298 HISTOSOLS is a eutrophic-peat with pH > 8.

299 All the other soil types present a mean of *r-max* over 0.4, and some of them are over 0.8

300 (REDUCTISOLS, REDOXISOLS, VERTISOLS, PODZOSOLS and ALOCRISOLS, for 5% of the

301 study site) and therefore not able to reduce N_2O (HV). Over 60 % of soil surface are classed in MV.

302 The BRUNISOLS (14 % of the study area) show *r-max* values ranging from 0 to 1.2. In fact, there are

303 two large categories of BRUNISOLS: Eutric BRUNISOLS and Dystric BRUNISOLS Dystric soils

304 have a base saturation (S/CEC: S being the sum of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+)) at

305 pH=7 of less than 50 % whereas Eutric soil have a base saturation at pH=7 of 50 % or more (Baize et

306 al., 2009). This soil attribute depends on the CEC and therefore has an influence on the *r-max* value.

307 Dystric BRUNISOLS have an *r-max* mean value upper than 0.8 and Eutric BRUNISOL have a *r-max*

308 value about 0.59, i.e. in the intermediate class.

309 There is also a large variability in *r-max* values of hydromorphic soils (COLLUVIOSOLS,

310 FLUVIOSOLS, REDOXISOLS and REDUCTISOLS), because these soils could be more or less

311 clayey and more or less acidic.

312 The value of the *r-max* seems to follow a growth in the direction of soil evolution through the

313 lateralization processes of clay lixiviation and acidification. Low-evolved soils (RENDOSOLS,

314 RENDISOLS, CALCOSOLS and CALCISOLS) have the ability to reduce N_2O to N_2, then soils that

315 move towards BRUNISOLS, LUVISOLS, PLANOSOLS lose their ability to reduce N_2O and finally

316 REDUCTISOLS and PODZOSOLS no longer reduce N_2O at all in N_2.

317 This soil evolution is described in soil Atlas of Europe in WRB classification. Cambisols degrade

318 because of vertical water erosion. The continuous leaching moves the calcium carbonate front further

319 downwards, the pH drops to about 6 and clay illuviation starts to become rich Luvisol. However, the

320 leaching will continuously remove the base elements from the soil. This will make the profile so acid

321 that it will be classified as an Alisol. At this stage the soil is so acid that the clay in the illuviated

322 horizon will disintegrate or be redistributed to other parts of the profile and tongues of silt and sand

323 will cut into the clay illuviated horizon. This is referred to as an Albeluvisol. Finally, the leaching will

324 enable an iron pan to develop and the soil turns into a Podzol.

325   3.1.2.r-max aggregation by SMU

326   SMU *r-max* maps joining data from RRPs and Donesol were carried out with the r-max mean of all

327   STU contained in the SMU weighted by their area (Fig. 5a) and using the soil variables of dominant

328   STU (Fig. 5b). There are many similarities between the two maps. The difference between Eastern and

329   Western regions can be explained by the presence of soils developed on limestone in Beauce/ Beauce

330   Dunoise (CALCOSOLS, RENDOSOLS, RENDISOLS, CALCISOLS) and the more acidic soils in

331   Western regions. Overall Western soils are not able to reduce N_2O. The highest *r-max* values are

332   located near the streams and in watershed heads of the Western-Perche/Faux Perche region

333   (REDUCTISOLS and LUVISOLS).

334   Figures 5c and 5d correspond, respectively, to the standard deviation calculated in the SMU and to the

335   representativeness of the dominant soil in the SMU. The maps show SMU with an *r-max* values > 0.8

336   in northeast (Beauce) and in southeast (Orléanais). In these areas, the *r-max* standard deviation is > 0.4

337   (Figure 5d). This suggests a large variation of *r-max* within the SMU due to differences between *r-*

338   *max* from grouped STU.
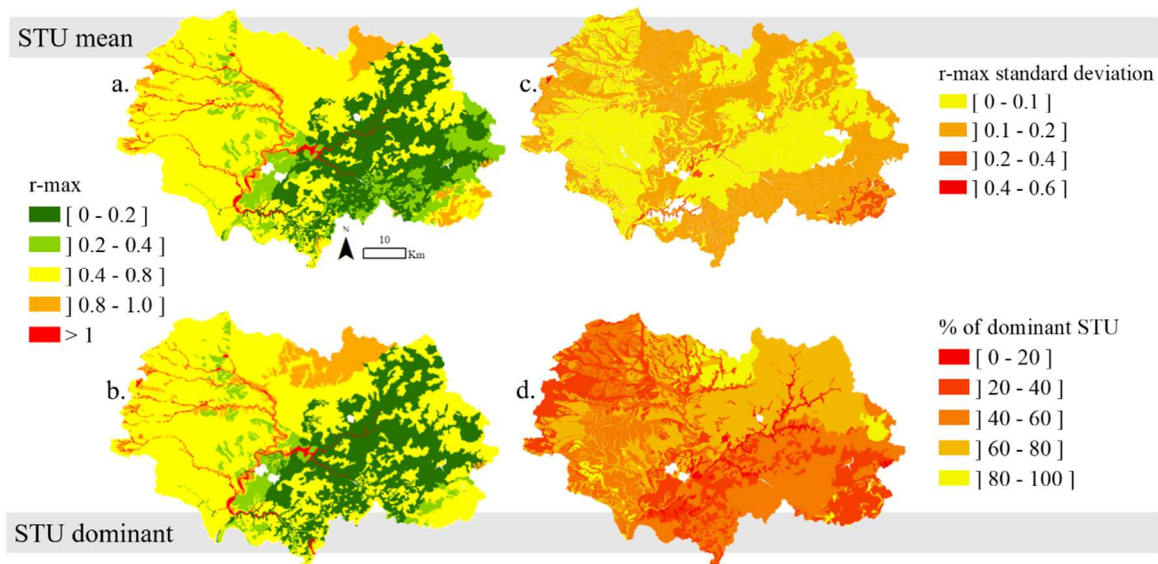
339

340   *Figure 5: r-max maps and related standard deviation at study site (Haut-Loir) (respectively with mean*

341   *and standard-deviation of all STU per SMU: 5a and 5c; and dominant STU values, 5b and 5d). See*

342   *text for more details.*

343 SMU aggregation allows to represent spatially the *r-max* at the expense of accuracy. The mean value

344 tends to smooth out extreme values and the dominant STU value is not always representative.
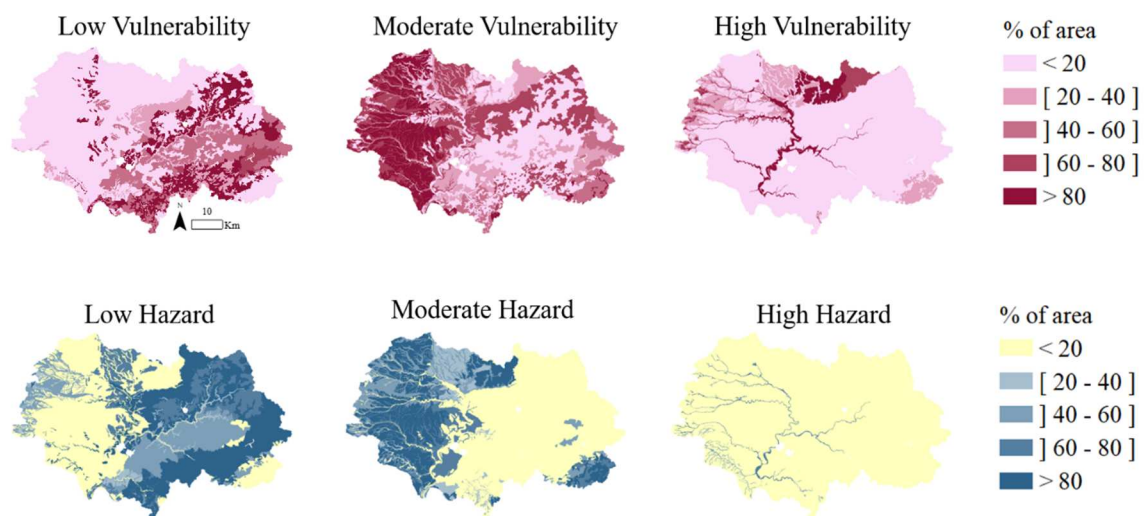
345

346   3.2. Risk assessment

347   3.2.1. Vulnerability and Hazard

348 Figure 6 exhibits the percentage of area of each SMU corresponding to the different Vulnerability and

349 Hazard typologies. This area was estimated based on vulnerability and hazard of the STUs forming the

350 SMU.

351

352 *Figure 6: Vulnerability and Hazard maps estimated at STU scale and expressed in percentage of SMU*

353 *area*

354 These maps allow to detect where the most vulnerable soils are located and those subject to the

355 greatest hazards. 15% of soil surface is not classified because of missing values. 29% of soil surface

356 from study site are classified in Low Vulnerability, 44% in Moderate Vulnerability and 12% in High

357 Vulnerability. 49% of soil surface are classified in Low Hazard, 35% in Moderate Hazard and 1% in

358 High Hazard.

359 Soils with Low Vulnerability and Hazard are mostly located in Eastern Beauce/Beauce Dunoise. Soils

360 with Moderate Vulnerability and Hazard are mostly located in Western Perce/Faux-Perche and

361 Orléanais and soils with High Vulnerability and Hazard are located in valleys.

362 Hazard and Vulnerability areas are quite similar. Non-vulnerable soils, therefore able to reduce N_2O to

363 N_2, seems not to have water excess characteristics. Conversely, vulnerable soils (MV and HV) are

364 generally in a situation of excess soil water (MH and HH). Indeed, excess water in the soil and

365 leaching induce redox processes and increase the soil acidity (Van Breemen and Buurman, 2002), so

366 these that two components are not always independent.

367 There are still a few special cases: the heads of watersheds on the Western side are classified in HV

368 and LH. There is also an area in North of the Beauce region that is classified in HV (because of low

369 pH value) and which is classified largely in LH.

370   3.2.2. Risk assessment by soil type

371 The risk of N_2O emission was assessed according to the soil type. The results are shown in Figure 7.
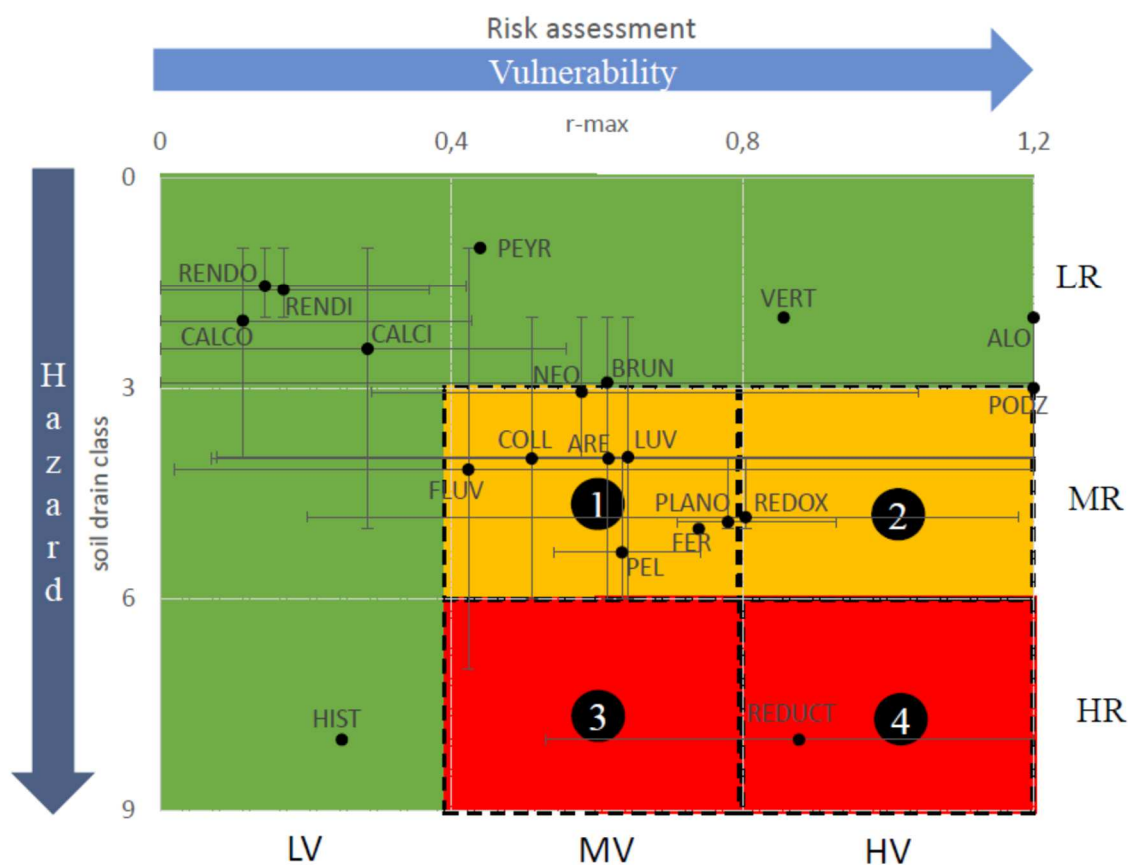
372

373 *Figure 7: risk by soil type based on their Vulnerability (mean r-max in x-axis) and Hazard ranges*

374 *(mean drainage class in y-axis)). Bars indicate the min-max values of both r-max values and drainage*

375   *codes for each soil type. For clarity only the first letters of the name of soil types is given; see Table 2*

376   *and text for the full name.*

377

378   Only REDUCTISOLS are in risk situation "4" and some of the FLUVIOSOLS which may be in a

379   significant situation of excess water are in risk situation "3". These two soil types are located in

380   wetlands that are currently protected from excessive nitrogen inputs. They are mostly occupied by

381   grasslands because the excess water does not allow cultivation.

382   Soils developped on limestone (CALCISOLS, CALCOSOLS, RENDISOLS and RENDOSOLS) do

383   not present any risk of N_2O emissions. HISTOSOLS, PEYROSOLS, VERTISOLS and

384   ALOCRISOLS have no risk either, but there is only one value available to characterize them.

385   PODZOSOLS have a High Vulnerability but the mean value of soil drain class is 3, thus the risk is

386   between Low and Moderate. Podzosols are very poor and very acidic soils that are not conducive to

387   agriculture.

388   All the others soils have a mid point in risk situation class "1" or "2". As soil types are generaly

389   composed of several STU, some STU may be at risk of N_2O emission and some others not, which is

390   illustrated in the Figure 7 by bars crossing the dashed risk line. Some of BRUNISOLS,

391   COLLUVIOSOLS, LUVISOLS, NEOLUVISOLS, PLANOSOLS and REDOXISOLS can be in

392   moderate risk category (situations 1 or 2) depending on their *r-max* values and usually of acidity.

393   High-risk situations of N_2O emissions are not necessarily found in cultivated areas and are therefore

394   not subject to high nitrogen Exposure. Indeed, very moist and acidic soils are not favourable to

395   agriculture.

396   3.2.3. Validation of the approach using a former dataset

397

398

399   Table 2 shows a very good consistency between N_2O emission and Calc. *r-max* index. However, some

400   discrepancy exists between Calc. r-max index and STU r-max index (Table 2). This is owing to soil

401   map resolution. Nevertheless, all soil types are within the same risk class as shown in Figure 7.

			Field measurements							Donesol database						
Site	Region	Period	N_2O emission (g-N /ha)	N input (kg N/ha)	Measured r-max index	pH	CEC (cmol +.kg^{-1})	Clay (g.kg^{-1})	Calcultated r-max index	STU name	pH	CEC (cmol +.kg^{-1})	Clay (g.kg^{-1})	STU r-max index	Drain. class	classr isk
Villamblain (1999)	Beauce Dunoise	Feb - June 1999	517	230	0.2	7.9	22.8	334	0.23	CALCISOLS	8	20.8	341	0.13	2	0
La Saussaye (1999)	Beauce	Feb - June 1999	376	164	0.2	7.8	16.5	242	0.2	BRUNISOLS	6.6	9.6	175	0.56	2	0
Arrou (1999)	Faux-Perche	Feb - June 1999	2855	173	0.6	6.23	2.9	50	0.66	LUVISOLS	6.7	9	140	0.54	4	1
SP1 (2014)	Faux-Perche	Feb - May 2014	696	142		7.1	7.24	125	0.35	LUVISOLS	6.7	9	140	0.54	4	1
SP3 (2014)	Faux-Perche	Feb - May 2014	950	140		6.8	9.82	181	0.48	COLLUVIOSOLS	6.4	12.7	250	0.65	5	1
SP5 (2014)	Faux-Perche	Feb - April 2014	986	170		7	9.11	145	0.42	LUVISOLS	6.7	9	140	0.54	4	1
SP6 (2014)	Faux-Perche	Feb - April 2014	2034	175		6.3	8.06	237	0.58	COLLUVIOSOLS	6.3	8.1	230	0.59	5	1
ND4 (2014)	Faux-Perche	Feb - April 2014	2781	175	0.66	6.3	6.81	141	0.65	COLLUVIOSOLS	6.4	12.7	250	0.65	5	1
SP2 (2015)	Faux-Perche	Feb - May 2015	740	231		6.4	6.82	140	0.61	LUVISOLS	6.7	9	140	0.54	4	1
SP4 (2015)	Faux-Perche	Feb - May 2015	933	220		6.5	9.82	137	0.65	COLLUVIOSOLS	6.4	12.7	250	0.65	5	1
SP5 (2015)	Faux-Perche	Feb - May 2015	314	230		7	9.11	145	0.42	LUVISOLS	6.7	9	140	0.54	4	1
SP6 (2015)	Faux-Perche	Feb - May 2015	293	230		6.3	8.06	237	0.58	COLLUVIOSOLS	6.3	8.1	230	0.59	5	1
ND4 (2015)	Faux-Perche	Feb - May 2015	2118	230	0.66	6.3	6.81	141	0.65	COLLUVIOSOLS	6.4	12.7	250	0.65	5	1
SP7 (2018)	Faux-Perche	Feb - May 2018	1550	240		7.2	9.7	118	0.4	LUVISOLS	6.7	9	140	0.54	4	1
SP8 (2018)	Faux-Perche	Feb - May 2018	1126	234		6.6	8.8	118	0.58	LUVISOLS	6.7	9	140	0.54	4	1
INRAE (2018)	Val de Loire	May - June 2018	200	100	0.61	6.23	2.9	50	0.66	BRUNISOLS	4.2	6.1	48	1.2	2	0

406
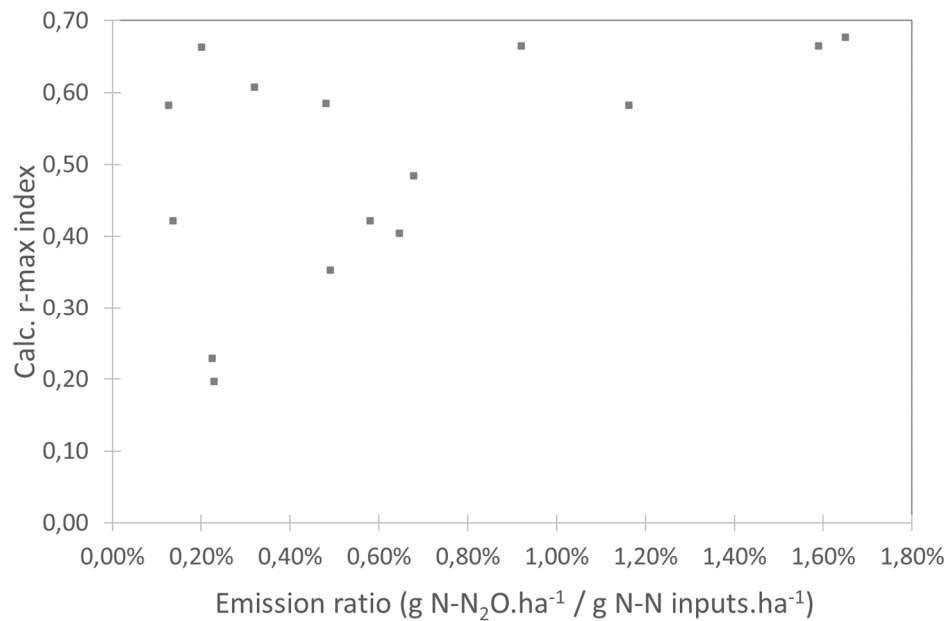
Figure 9 : r-max index calculated based on measured soil properties versus emission ratio during
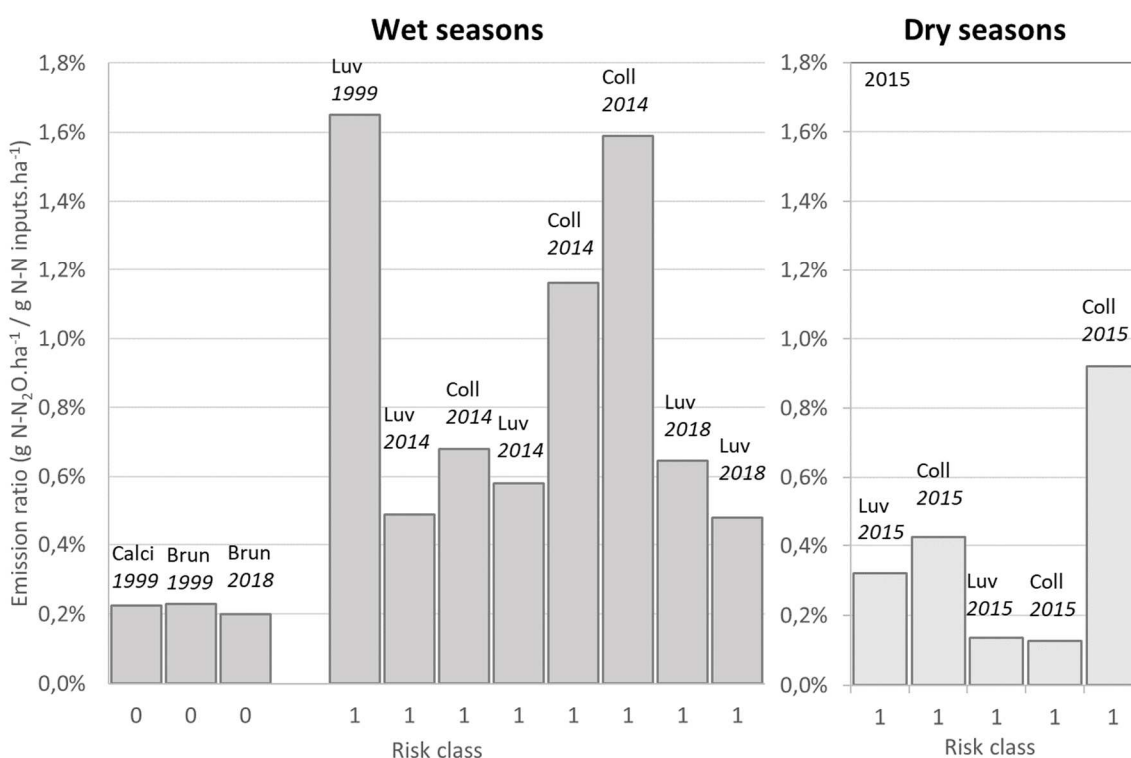
post-fertilization period.

The risk class for each site was estimated (table 2). Only three sites were classified as risk class 0 (no

risk). One of them presented both low hazard and low vulnerability (Villamblain site) while the two

others presented medium vulnerability but low hazard (good drainage class) resulting in low emission

risk. For one of these sites, (La Saussaye) this was not consistent with direct observations because a

small r-max index was measured.

A risk class 1 was found for ten sites, corresponding to thirteen N_2O emission values (three sites were

sampled in both 2024 and 2015). This could be explained by the fact that an area known for its

emissions is usually selected for such studies. There may therefore be a bias in favor of soils at risk

when choosing sites. However, no risk class greater than 1 was found.

To assess if soil classified as "at risk" indeed present largest N_2O emission, Figure 10 shows the ratio

of cumulated N_2O emission on N inputs during fertilization and post-fertilization period as a function

of class risk. During wet seasons, the ratio of N_2O emission on N input was smaller on sites

presenting no risk (about 0.2%) than on sites presenting a risk class 1. Sites having a risk class 1

21

423 showed a large variability of the emission ratio, but it was always larger than 0.4%. In 2015, which

424 was a rather dry year, only sites having a risk class 1 were studied. The emission ratio also presented a

425 large variability but it was smaller than during wet seasons and some sites even presented emission

426 ratio as low as the no risk sites during wet years. This is consistent with the hypothesis that risk is

427 associated to hazard more than vulnerability because in dry conditions, even in hydromorphic soils,

428 there is little denitrification.

429

430

431 *Figure 10: N$_2$O emission ratio versus soil risk class. Emission ratio is calculated as the ratio of*

432 *cumulated emission of N$_2$O during fertilization and post-fertilization period on N inputs and soil risk*

433 *class is assessed through Donesol variables of the corresponding STU (see methodology part for more*

434 *details). Left: observations made during wet climatic years, right: observations during normal to a dry*

435 *climatic year. Emissions were cumulated over the fertilization periods, thus corresponding to different*

436 *intervals (see Table 2).*

437   3.2.4. Risk mapping

438   Figure 8 (top) presents the percentage of area that present a risk of N_2O emissions, and on the other

439   maps (Figure 8, bottom), the risk is declined in the 4 situations described in Figure 4.
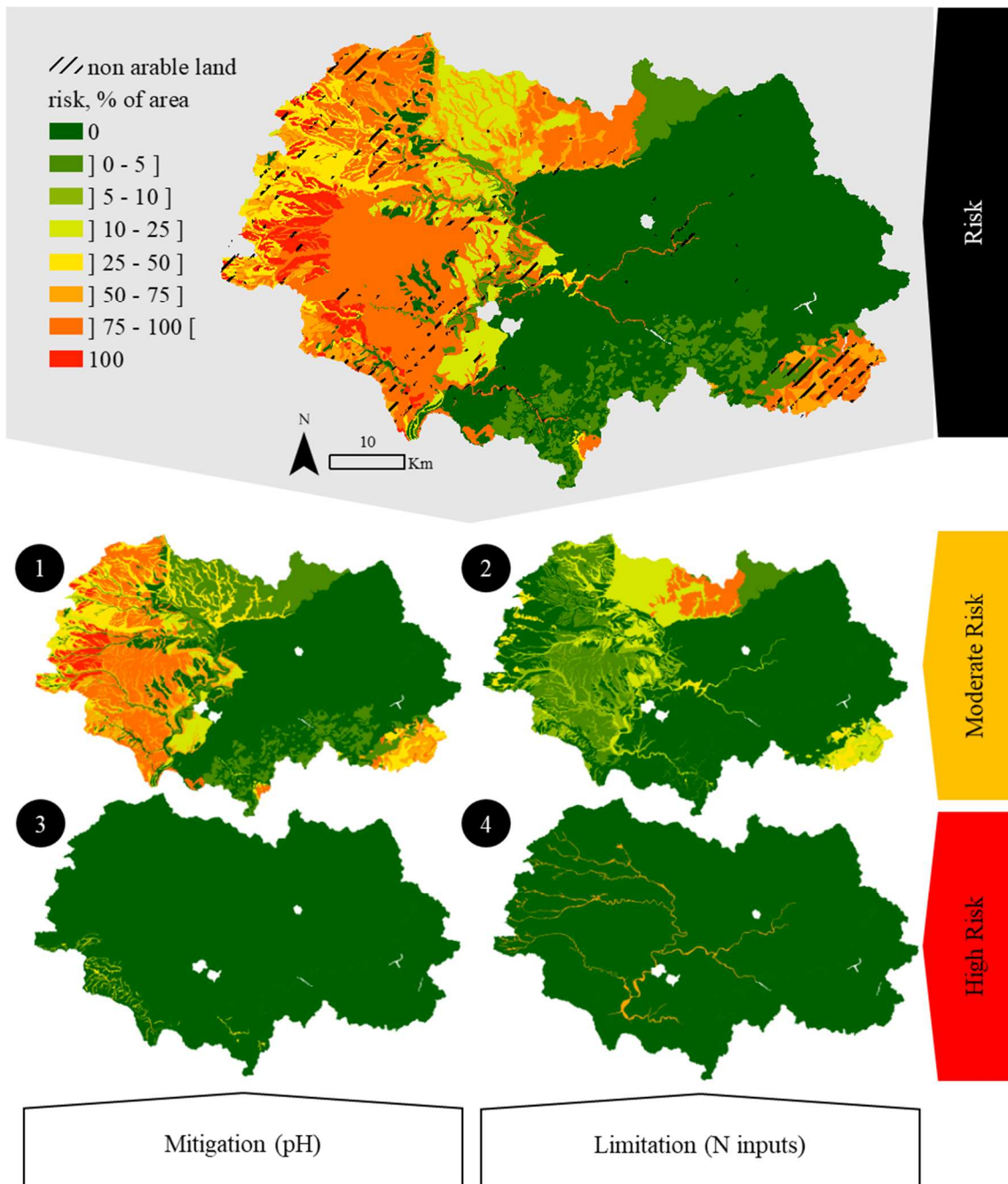
440

441   *Figure 8: Top. map of the relative area presenting N_2O emission risk; bottom: maps of relative area of*

442   *each emission risk categories 1, 2, 3 and 4. For risk category definition, see Figure 5.*

443   The risk situation is undefined for 15% of the total area. 53% of the surface present no risk of N_2O

444   emissions conversely to 32% of the total area. These 32 % can be split into 4 situations: 24 % in 1, 6%

445   in 2 , less than 1% in 3 and 1% in 4. Most of these risky soils are located in the Western Perche/Faux

446   Perche region, where 12% of the surface is covered by forest. Part of risky soils is also located in the

447   Orleans forest (Orléanais region), but these soils are not exposed to nitrogen inputs, risk does not exist

448   without exposure.

449   3.2.5. Uncertainties and strengths of the present approach

450   This approach of mapping emission risk can present several limitations. Firstly, as already written for

451   hazard and vulnerability maps, SMU aggregation entails uncertainties on the final risk map. To check

452   how reliable the two aggregation methods were, the risk for validation site was also estimated based

453   on SMU and not true STU (see supplementary material). Both SMU aggregation methods gave the

454   same risk class than the true STU corresponding to the sites. The methodology used for soil

455   classification also present uncertainties. The protocol for the *r-max* index measurements is based on

456   incubation with acetylene. The acetylene method can underestimate denitrification and ratio

457    $N_2O/(N_2O+N_2)$ because of several reasons, e.g. low diffusion of acetylene in intact soils and inhibition

458   of nitrification in field conditions (Groffman et al., 2006) so field assessment may be biased. The

459   present index is measured in artificial conditions: soil slurry amended with nitrate under agitation:

460   these conditions provide an index of the soil capacity of reduction to N_2 and not a direct measurement.

461   Reduction of N_2O to N_2 can also be influenced in the fields by the soil nitrate and carbon availability

462   (Senbayram et al., 2012). However, the *r-max* index measured in the laboratory has been shown to

463   relate well with field N_2O emissions (Hénault et al., 2005; Hénault et al., 2019). Last, only natural

464   drainage class from Donesol database was considered to define the hazard. Soil hydromorphy effect on

465   N_2O emission can however be highly impacted by management practices: e.g. tile-drainage (Grossel et

466   al., 2016), tillage (Rochette et al., 2008), soil compaction (Pulido-Moncada et al., 2022).

467   The approach was evaluated by comparison with a limited database from in situ measurements and it

468   would be interesting to have further field data for validation. Moreover, field data also present

469   uncertainties : emissions were measured by manual static chambers and cumulative emissions has an

470   uncertainty linked to the frequency of measurements (Smith and Dobbie, 2001). Observed variability

471   is linked to the soil moisture dynamics, which is controlled not only by the precipitation regime but

472   also the vegetation, tillage, and soil hydromorphy itself which can be due to the presence of a deep

473   clay layer, position in topography (foot slopes) or contact with a water table. This can be illustrated by

474   the site 5 (Franqueville et al., 2018) which was measured in 2014 and 2015. It was close to an

475   intermittent river and soil hydromorphy is due to this vicinity (river water table). In spring 2015 the

476   river dried out and N_2O emissions ratio on N input was very low, while it was large in spring 2014.

477   Last the variability of emissions is also controlled by the timing of fertilization and precipitations. The

478   classification does not discriminate all field conditions but observations are consistent with the

479   assessed soil classification for N_2O emissions risk, suggesting that it can help distinguishing between

480   risk level 0 and 1.

481   N_2O emissions are controlled by a complex interplay of many factors, resulting in large variations both

482   in time and space. N substrate is the main factor so many mitigation solutions have focused on

483   applying N at optimal rate to limit surplus, using enhanced efficiency fertilizers, including nitrification

484   inhibitors or introducing legumes in rotations (Luo et al., 2019; Kanter et al., 2020; Wagner Riddle et

485   al., 2020). Although some solutions will benefit to any soil or climate type (such as health diet habit,

486   Luo et al., 2019), identifying the riskiest areas for N_2O emissions is also needed to target mitigation

487   efforts (Cui et al., 2021). Site-specific management is proposed to mitigate local hotspots of N_2O

488   emissions but it has yet to be tested how this approach can apply at regional scale (Wagner-Riddle et

489   al., 2020). This study proposes thus an approach to identify possible risk areas. This approach is based

490   especially on a risk classification by soil types; soil type has indeed been long recognized as a control

491   factor of N_2O emission (Robertson 1989).

492   Identifying the risk factors could help proposing mitigation strategies. For 3/4 of the risky situations

493   (risk classes 1 + 3), N_2O emissions could be mitigated by regularly liming soil to maintain a pH

494   around 6.8, as suggested by Hénault et al. (2019). Liming can have beneficial effects by reducing N_2O

495   emissions, while it can also increase agronomic risk (defficiency) and CO_2 emissions, but a recent

496   meta-analysis suggested that, because of general yield increase, it may be beneficial (Zhang et al.,

497   2022). Management based on liming should therefore still be assessed by local studies (Hénault et al.,

498   2019) and the present approach can also serve to guide where to conduct such studies. A third of other

499   soils (risks 2 and 4), require a liming so-called "redress" action to avoid any risk. A soil drainage

500   action does not prevent temporary water excess, but just limit this duration. It is best to avoid exposing

501   soils to risk in too wet soil situations by not providing nitrogen. Farmers can predict these situations

502   through the weather forecast or using soil moisture sensors. Theses situations are located at the edge of

503   streams (The Loir and its tributaries), in areas with REDUCTISOLS and FLUVIOSOLS. It is not

504   advisable to fertilize these soils areas, which are often classified as wetlands and which also cause

505   problems with nitrate pollution.

506   The patterns of the risk map (Figure 8) are consistent with those of Lugato et al. (2017), who mapped

507   mean N_2O emission simulated on five years (supplementary material). Their map also showed two

508   contrasting N_2O emission areas with values from 1.09 kg N ha^{-1} yr^{-1} to 3.8 kg N ha^{-1} yr^{-1} for 2010 to

509   2014 at Haut-Loir. The added value of current paper is that it proposes maps of emission risk provided

510   by soil types, rather than N_2O emission, which are dependent on temporal variables such as

511   precipitation regimes and agricultural practices. This enables also to propose action to be taken

512   according to the risk situation. The *r-max* value (computed from soil clay content, CEC and pH)

513   associated with a soil water excess indicator, available in French soil database, seems to be an efficient

514   approach to define soil situations that require special care and help farmer to identify risky situation.

515

516   **Conclusion**

517   A methodology to map N_2O emission risk at regional scale based on soil properties was developed.

518   Risk was defined by crossing a "vulnerability", defined by the low capacity of soil to reduce N_2O in

519   N_2 during denitrification, and "hazard", defined by the probability to have water excess and directly

520   linked to soil drainage class. In the Haut-Loir watershed, 32% of soils presented N_2O emission risks

521   (when exposed to nitrogen fertilization), of which 75% could be mitigated by liming. Some soils

522   (mainly the REDUCTISOLS in the valleys and some hydromorphic LUVISOLS), covering 7% of the

523   watershed area, would require moreover special attention in nitrogen inputs. As the method is based

524   on knowledge of well-known factors controlling N_2O production and reduction by denitrification and

525   as these data are accessible in soil databases, i.e. drainage class, pH, CEC and clay content, it could be

526   also applied to other regions. These risk maps can allow decision-makers to identify agricultural areas

527   that require special precautions to reduce agricultural N_2O emissions.

528   Acknowledgements

533   **Appendix A : soil correspondance RP 2008 to WRB 2006**

RP 2008	*WRB 2006*
ALOCRISOLS	Cambisols Hyperdystric
ARENOSOLS	Arenosols
BRUNISOLS	Cambisols Eutric or Dystric
CALCISOLS	Cambisols Hypereutric
CALCOSOLS	Cambisols Calcaric
COLLUVIOSOLS	Colluvic Regosols
FERSIALSOLS	Haplic Luvisols
FLUVIOSOLS	Fluvisols
HISTOSOLS	Histosols
LUVISOLS	Haplic Luvisols or Haplic Albeluvisols or Luvisols
NEOLUVISOLS	Luvic Cambisols
PELOSOLS	Epistagnic regosols or Vertic Cambisols
PEYROSOLS	Hyperskelectic Leptosols or Hyperskelectic Podzols
PLANOSOLS	Planosols
PODZOSOLS	Podzols
REDOXISOLS	Stagnosols
REDUCTISOLS	Gleysols
RENDISOLS	Epileptic Cambisols Calcaric
RENDOSOLS	Epileptic Cambisols Hypereutric
VERTISOLS	Vertisols

534

535

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